Spatial and Temporal Variation in a Perched Headwater Valley in the Blue Mountains: Geology, Geomorphology, Vegetation, Soils and Hydrology

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Geology, geomorphology, vegetation, soils and hydrology were examined in an eight year study of spatial and temporal variation in a perched headwater valley in the Blue Mountains, New South Wales, Australia. Data were collected at a series of fixed sites.

Geology is important in the development of the valley form and landscape. The dominantly sandstone rocks have intercalated claystones which act as aquicludes. The claystones control the valley-in-valley segmentation and the movement of groundwater which in turn results in the development of swamps.

Geomorphic features identified included valley asymmetry, fill-incision transition zone, oversteepened reach, understeepened reach and amphitheatre. Other features defined and described for the first time in the Blue Mountains are alluvial bulges, ephemeral and perennial swamps, and valley-side knickpoints.

Three vegetation units were identified and aligned with a drainage related gradient. These are woodland dominated by trees of *Eucalyptus piperita* and *E. sclerophylla*, ephemeral swamp with sedges of *Lepyrodia scariosa* and perennial swamp with clumps of *Gymnoschoenus sphaerocephalus*. Aspect differences were measured for tree basal area and understorey diversity. Post-fire trends in cover and diversity were measured.

Soil depth was shown to vary with aspect, as was ground water depth, which also varied with vegetation type. Valley asymmetry is evident in the soils, vegetation and hydrology.

Hydrology (surface flow and groundwater movement) varies in response to rainfall regimes, and to differences in evaporation on a yearly, seasonal, daily and hourly basis. The amount and direction of groundwater flow is largely controlled by the claystones. Hydrological patterns in the woodland and ephemeral swamps differ markedly from those in the perennial swamp.

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INTRODUCTION

Because of the complexity of natural systems, landform studies either emphasize individual elements or generalize on a range of aspects using limited data. There is rarely the opportunity to study a wide range of aspects of a natural system in depth. Holland (1974) related the geomorphology of the upper Blue Mountains of New South Wales to the underlying stratigraphy and drew attention to the importance of headwater valleys — renamed here 'perched headwater valleys' — as small, discrete and easily identifiable landforms. This provides a firm base for the further exploration of spatial and temporal variations in a typical perched headwater valley.

The study area chosen, Cold Foot Creek (lat. 33°40′S, long. 150°21′E., 11.3 ha, 900 m elevation) (Fig. 1) is a typical perched headwater valley with undisturbed natural vegetation and east-west oriented drainage which allows ready comparison of aspect differences. It includes a major swamp surrounded by woodland. There are no obvious signs of human disturbance other than Mt Hay Road and a disused side track.

This paper attempts to integrate various aspects of the geology, geomorphology, soils, vegetation, and hydrology in terms of spatial and temporal patterns. A further study (Holland *et al.*, 1992) looks at the influence of solar radiation and temperature on the valley environment.

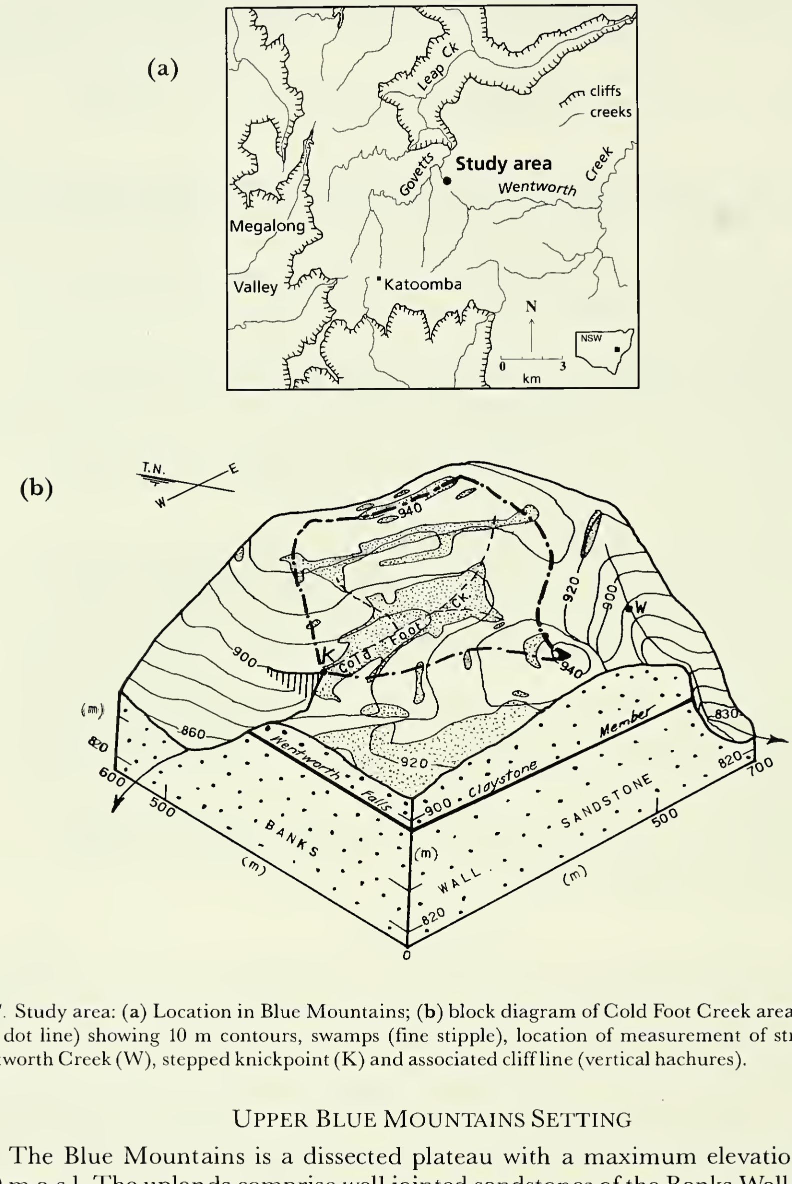

Fig. 1. Study area: (**a**) Location in Blue Mountains; (**b**) block diagram of Cold Foot Creek area (enclosed by dash dot line) showing 10 m contours, swamps (fine stipple), location of measurement of stream flow on Wentworth Creek (W), stepped knickpoint (K) and associated cliff line (vertical hachures).

Upper Blue Mountains Setting

The Blue Mountains is a dissected plateau with a maximum elevation of about 1100 m a.s.l. The uplands comprise well jointed sandstones of the Banks Wall Sandstone with intercalated shales and claystones (Goldbery, 1966; Goldbery and Holland, 1973). Regional dip is generally easterly at about 1° and primary joints bear 175° (true north) with a secondary direction of 65° (Holland, 1974).

Valley width/depth ratio decreases downstream for all the valleys i.e. they tend to deepen rather than widen, many becoming slots (Holland, 1977). Creek incision includes the development of stepped knickpoints which form in response to differential erosion of the rocks and migrate upstream along individual claystone beds. Their rate of headward erosion slows upstream as drainage basin area diminishes and the amount of water available for erosion becomes less.

Perched headwater valleys are upstream of the first stepped knickpoint below a basin divide. These upland valleys have smooth, gentle slopes and minimal cliff development and contrast with a small number of other valleys in the headwaters without stepped knickpoints but with steep valley sides and cliffs extending close to the divide.

Holland (1974) noted that knickpoints occur where claystone outcrops on the valley sides. They mark the limits of individual valley segments which together form a valley-in-valley landscape. There is usually ferruginized sandstone above a claystone outcrop which obscures it. The hard ironstone probably results from long term movement and evaporation of iron-rich water. Slopes above the claystone are generally less steep than below it. The resistant ironstone facilitates a decrease in the upper slopes while allowing the lower slopes to steepen by slowing the rate of horizontal retreat of the knickpoint. The upper margins of swamps lie along the tops of the claystone beds. These swamps have sedgeland vegetation, part of the 'Blue Mountains Sedge Swamps' unit (all vegetation units are as in Keith and Benson, 1988). The swamps in the perched headwater valleys contain sandy-peaty soils which average 1.2-1.5 m in depth (Holland, 1974). Above a claystone outcrop the ground is usually dry, with woodland cover of the 'Blue Mountains Sandstone Plateau Forest' unit and has trees of *Eucalyptus sclerophylla*, *E. sieberi* and *E. piperita*. These swamps, whose upper edges are controlled by the claystones should not be confused with the dells identified by Young (1982) which have no such geologic control.

Perched headwater valleys tend to have longitudinal profiles which are understeepened compared to headwater valleys with no stepped knickpoints and to a model profile developed by Holland (1974). Slopes facing slightly east of north tend to be less steep than those facing west of south (Holland, 1968, 1974; Stockton and Holland, 1974). Such valley asymmetry has been widely observed elsewhere (Thornbury, 1954).

Methods

Cold Foot Creek Study

A range of geomorphic features were sampled at 31 sites (Fig. 2**a**, **b**) between September 1980 and December 1988. The sites were connected by a traverse and height, aspect and slope were recorded. Slopes were measured below each site and along selected contours on both valley sides, equally high above the creek. Joints were measured near the stepped knickpoint, at the end of the valley. Identification and measurement of ground features was aided by mapping one metre contours using photogrammetric and stadia methods.

Vegetation data were collected from sites 1-30. The girth of trees in 20 x 20 m plots at each site was recorded in December 1980. Also at this time the plant species in each quarter of a 2 x 2 m sampling site at the centre of each 20 x 20 m plot, were recorded. The species sampling included an estimate of the projective foliage cover of each species.

A bushfire burnt the entire valley in December 1982 and the species were re-recorded twice in the manner outlined above, in February 1984 and September 1985. The data from the pre-fire recording (95 species from 30 sites) were analysed using a TWINSPAN classification (two way indicator species analysis) and DECORANA ordination (detrended correspondence analysis and reciprocal averaging) (Gauch, 1982).

Soil samples were taken by augering to bedrock at each site. Additional soil depths

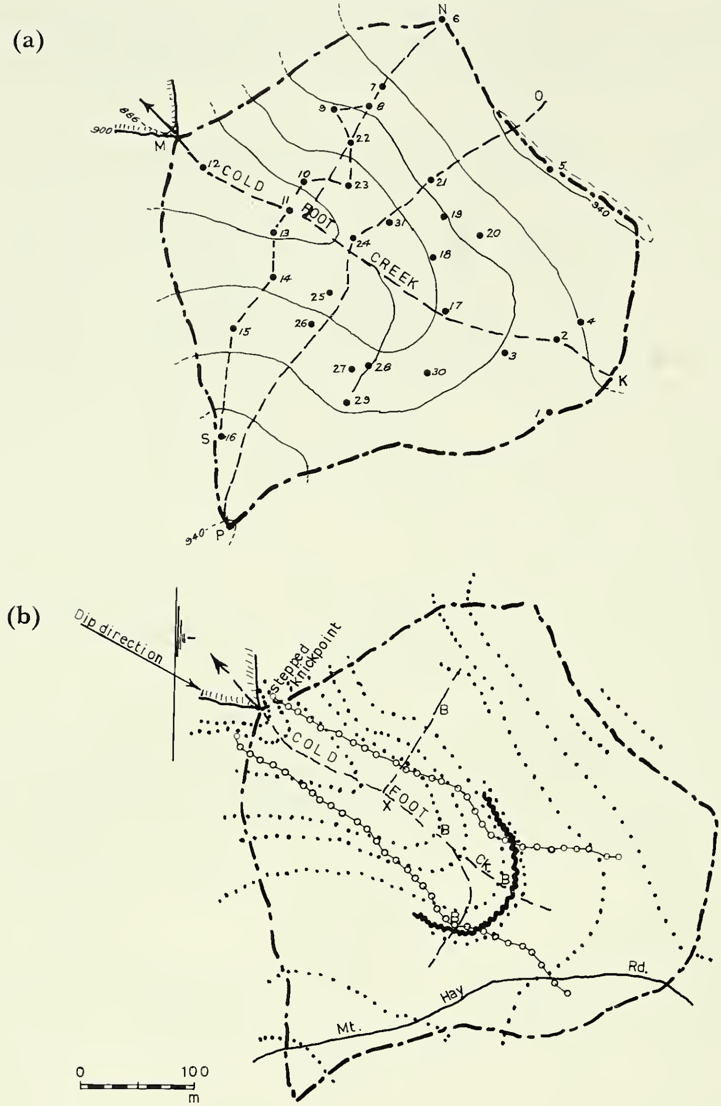

Fig. 2. Study area (dash/dot line) showing: (**a**) contours (8 m interval), sections K-M, S-N, P-O (dashed lines) and sites (numbered solid circles); (**b**) important geomorphic features — valley-side knickpoints along inferred claystone beds (line of dots), valley width/depth (points taken 3 m above, and normal to thalweg) (line of open circles), alluvial bulge (B), understeepened reach (X) and amphitheatre (wavy line).

were measured using 15 mm and 30 mm diameter pointed mild steel bars along sections K-M (Fig. 3**a**) and P-O (Fig. 3**b**). Surface moisture for each site was compared using a horticultural soil tester. Precise values of the units are unknown and were not needed since comparisons only are required. Data were recorded at about monthly intervals (September 1985-December 1987). Additional hourly records were made during several days in June and December of 1987 and 1988.

Stream discharges were recorded at the stepped knickpoint (September 1980-

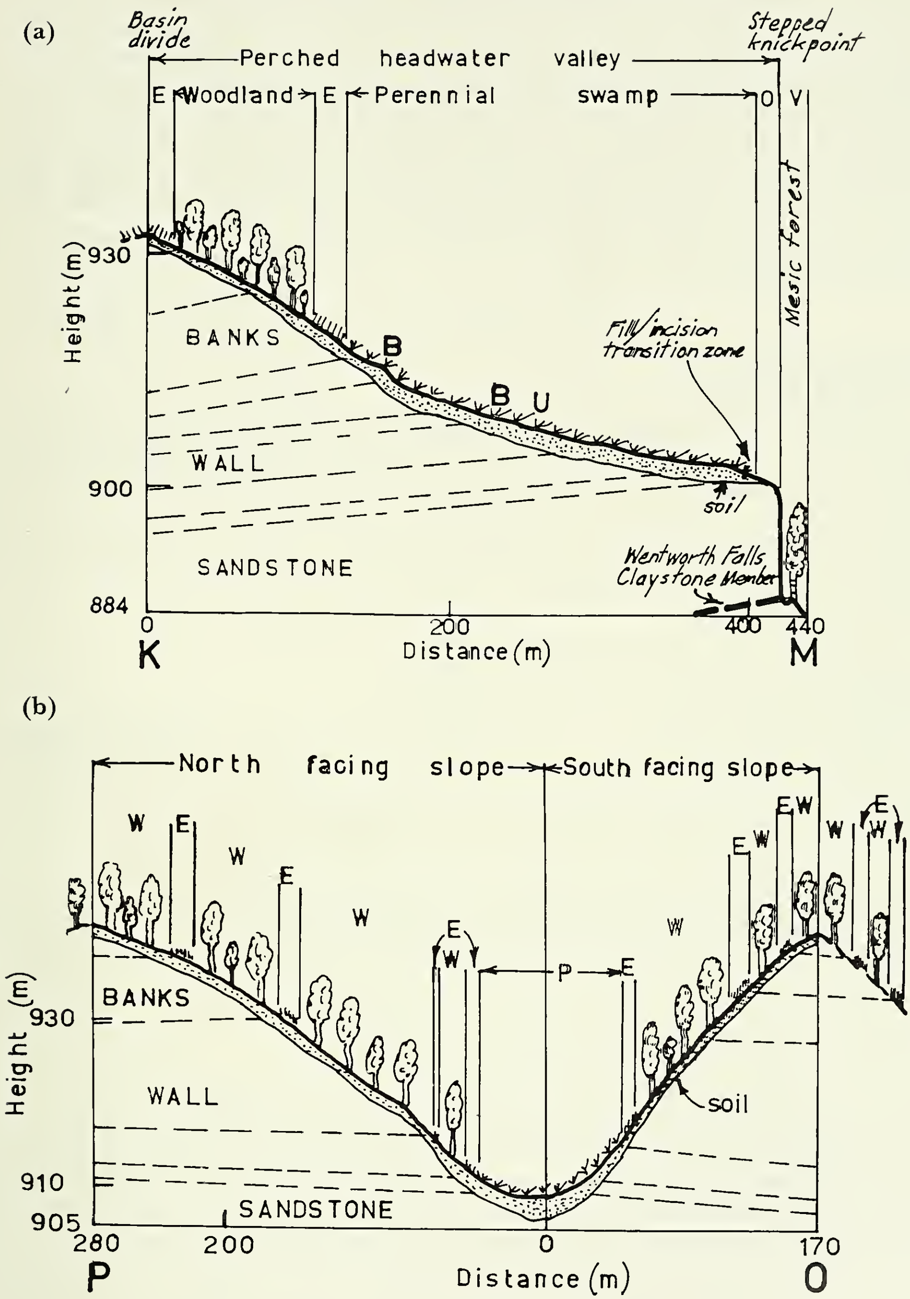

Fig. 3. Sections of valley: (a) longitudinal profile of Cold Foot Creek (K-M, Fig. 2a) showing stratigraphic, geomorphic and vegetation features (E = ephemeral swamp, B = alluvial bulge, U = understeepened reach, O = oversteepened reach, V = entrenched valley) — inferred claystone beds shown by dashed lines; (b) cross section (P-O, Fig. 2a) showing stratigraphic, geomorphic and vegetation features (W = woodland, E = ephemeral swamp and P = perennial swamp).

December 1988) at about monthly intervals. Discharges were measured by diverting the flow at the lip of the knickpoint where it flows over bare rock. Sand filled plastic tubes diverted the water into a container where the flow was timed. Additional continuous records of flow, extending over several days, were obtained with a mechanical recorder.

Groundwater movement was measured in a 45 mm dia. perforated plastic pipe — a single pipe was sunk to bedrock at each site (except 3, 27 and 30). Water levels were recorded at about monthly intervals from March 1982 to December 1987. Additional records of hourly measurements were made during surveys in June and December 1987. Continuous records extending over several days, were made at site 10 with an automatic recorder in December, 1987.

RESULTS

Geology and Geomorphology

Spatial Variation

Rock is not visible, apart from ferruginized sandstone less than a metre high, exposed at some valley-side knickpoints and at the stepped knickpoint. Claystone is seen only in road cuttings. Additional beds are inferred from the known relationship between the tops of swamps and claystone beds (Fig. 3**b**). Regional dip, calculated from planes of best fit on the tops of the swamps, varies from 0.8° to 1.6° and the direction of dip from 91° to 119° (based on true meridian). These results are consistent with findings of Holland (1974).

Primary joints near the stepped knickpoint averaged 160° with a secondary set averaging 70°. The joints are numerous and deep.

The valley has smooth, gentle slopes which are generally concave on the valley floor and convex further upslope. There are no cliffs, apart from the characteristic stepped knickpoint (Holland and Pickup, 1976), developed on the Wentworth Falls Claystone Member, at the end of the valley. The mean slope of south-facing sites is significantly greater than those facing north (Table 1). As significant differences are evident in woodland and swamps, slope differences are independent of vegetation cover.

The longitudinal profile traverses the thalweg since the creek is largely unformed. The grade changes where inferred claystones crop out along the thalweg — below these points it is steeper than above them. They could be relict stepped knickpoints smoothed by erosion.

An oversteepened reach (i.e. steeper than Holland's (1974) model profile of Blue Mountain creeks) of 11 m length (Fig. 4), occurs immediately above the stepped knickpoint where bare rock is exposed (Holland and Pickup, 1976).

A fill-incision transition zone is the interface between the upstream limit of erosion of bedrock at the knickpoint (oversteepened reach) and the creek flowing in fill upstream of it. Both field observations (Holland, 1974) and experiments (Holland and Pickup, 1976) have demonstrated that the position of the zone can fluctuate. As the soil here is thinner than further upstream the zone is vulnerable to climatic factors which alter the binding vegetation and roots or to hydrologic factors which affect the erodibility.

An understeepened reach (Fig. 4), results from processes balancing rates of valley widening and deepening above the knickpoint. The concave profile here also incises a number of claystones whereas the claystones further downstream are more widely spaced because of the gentle creek gradient. Thus subsurface water emerges at a number of points on the understeepened reach, possibly aiding bedrock corrosion (Bunting, 1960).

New features on the longitudinal profile are called here *alluvial bulges* (e.g. at sites 8, 17 and 24). These occur below abundant supplies of subsurface water from claystone bed outcrops. The emerging water increases the plasticity of the soil and over a long period adds sediment in suspension to supplement that transported from further upstream. The net result is a bulge in the profile, slumping downstream and ridges and swales normal to the ground slope. The swamps have numerous sediment traps of vegetation and soil up to 0.2 m high and ridges and swales, similar to those described by McElroy (1952), up to 0.5 m deep. These ridges, of living *Gymnoschoenus* tussocks and trapped sediment, are normal to the slope. These features divert the flowline, dispersing water over a wide area and protecting the valley floor from erosion.

An amphitheatre is formed at the head of the swamp (near site 17). Factors affecting the development include headward retreat of the knickpoints and valley-side knickpoints, junction of two thalwegs, oversteepening of the valley sides below valley-side knickpoints and understeepening of the valley floor.

Width/depth values for 3 m above the valley floor are consistent with Holland's (1974) regression equation (w/d = 94.85-30.22 log D, where valley width (w) is 3 m above the creek, valley depth (d) is 3 m, distance (D) below the interfluve is in metres, number of observations (n) is 15, and coefficient of determination (r^2) is 0.95). Valley width (w) also narrows downstream.

TABLE 1

Mean Slope (°) ± s.e.m., showing comparison of north and south-facing slopes

	N-facing		S-facing		
		n		n	
All sites	6.2 ± 0.55	14	9.7 ± 0.79	17	t = 3.4 P<0.005
***Woodland**	7.7 ± 0.13	19	11.4 ± 0.96	19	t = 3.7 P<0.001
***Ephemeral swamp**	12.4 ± 0.57	17	16.8 ± 0.58	23	t = 5.1 P<0.001
***Perennial swamp**	6.6 ± 0.64	17	8.8 ± 0.94	21	t = 5.5 P<0.001

* Slopes taken opposite each other and equally high above the creek for each vegetation area.

Temporal Changes

Landforms generally are the end result of long-continuing and distant processes. Recognition of time differences is often largely speculative. Alternatively, testing small-scale differences is complex and time-consuming. This study has not examined these differences.

Vegetation and Soils

Spatial Variation

The most notable feature of the vegetation is the distinction between the eucalypt woodland and the treeless sedgeland and shrubby heath of the swamps (Fig. 5). The contrasting vegetation areas are clearly apparent in aerial photography and in most cases the transition from woodland to swamp is abrupt. The major swamp, Cold Foot Swamp, of about 1.7 ha, extends above the stepped knickpoint for some 280 m with a maximum width of 100 m. At the beginning of the study the sedgeland, was dominated by sedges and small shrubs, particularly by *Gymnoschoenus sphaerocephalus* (Button Grass) and *Xyris operculata*. Around the margins was a fringe of *Hakea teretifolia*. The woodland has trees of *Eucalyptus sclerophylla*, *E. sieberi* and *E. piperita*.

The pre-fire TWINSPAN classification identified three species groups (Fig. 6). A group characterized by *Gymnoschoenus sphaerocephalus*, *Baeckea linifolia* and *Empodisma minus*, associated with the wettest swamp sites, a second group characterized by *Lepyrodia scariosa*, associated with marginal swamp conditions, and a third group with *Lambertia*

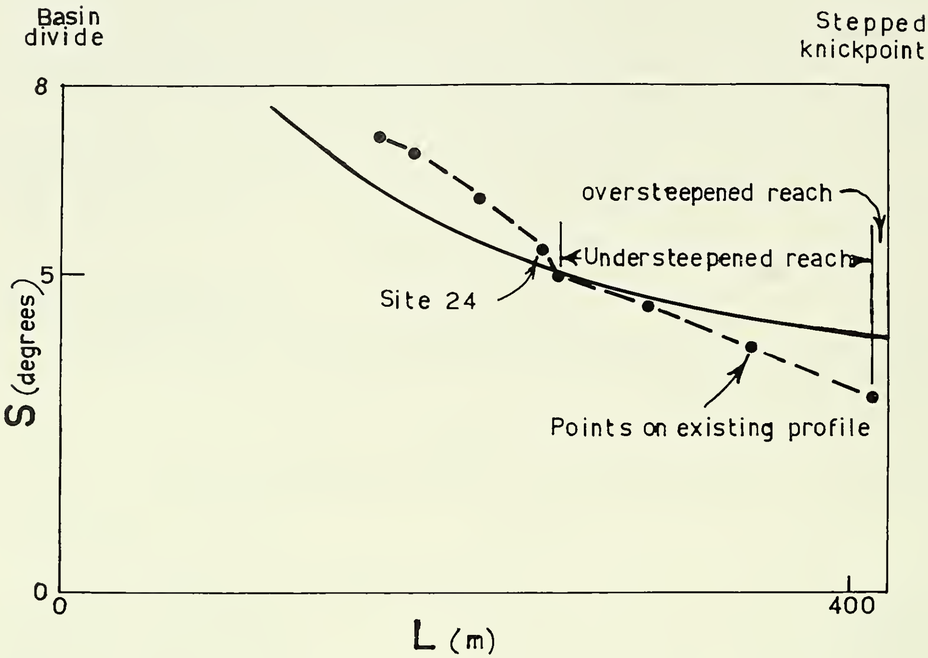

Fig. 4. Longitudinal profile of Cold Foot Creek (dotted line) compared to model profile of Holland (1974) $S = 2.11\ (0.006\ L)^{-0.474}$ (solid line) where S = slope (°) and L = distance from the basin divide (m).

formosa, *Daviesia ulicifolia* and *Patersonia glabrata* was indicative of woodland sites.

The DECORANA ordination showed the three groups to be aligned strongly with the first axis which appears to indicate increasingly better drainage conditions from Group 1 swamp species to Group 3 woodland species.

Soils are shallow, sandy, and contain organic material from rotting vegetation and charcoal from bushfires. Woodland soils are generally yellowish in colour with little contained organic material; ephemeral swamp soils tend to be grey/brown with some organic material in the profile; while the soils in perennial swamps are usually grey/black and contain large amounts of organic material throughout the profile. Soil depth means are higher for the perennial swamps than for the ephemeral swamps and the results are significant (Table 2a). The means are also higher for the perennial swamps than the woodland and these results are significant.

Floristic differences between vegetation on the north and south-facing slopes were evident in data collected from the woodland sites (Table 3). Total tree basal area is highest on south-facing slopes. Of the tree species, *Eucalyptus piperita* makes up about half basal area on both north and south-facing slopes, on north-facing slopes *Eucalyptus sclerophylla* is the other major species, on south-facing slopes dominance is shared between *E. sclerophylla* and *E. sieberi* (Table 4).

In comparison with tree predominance on the south-facing slopes, the shrub and ground species flora is richer on the north-facing slopes and has greater total cover (Fig.

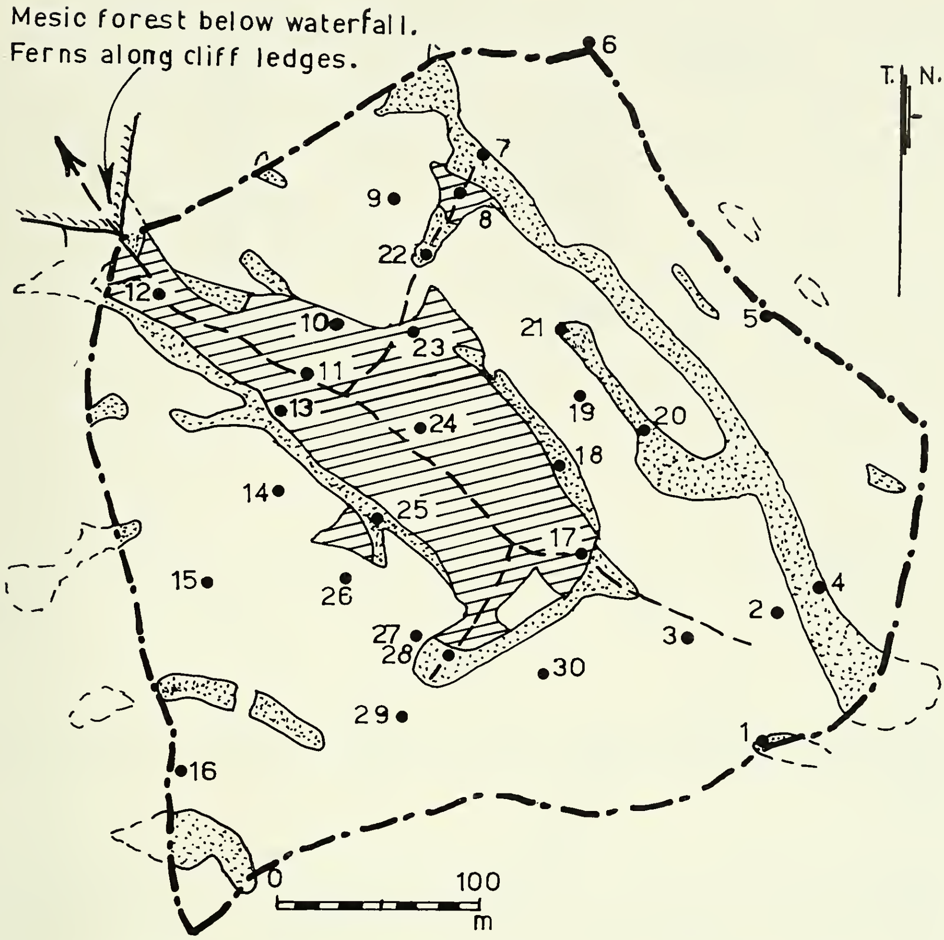

Fig. 5. Vegetation map showing woodland dominated by *Eucalyptus* (unshaded), ephemeral swamp by *Lepyrodia* (stippled) and perennial swamp by *Gymnoschoenus* (hatched), together with vegetation sampling sites.

TABLE 2

Mean soil depth (m) (± s.e.m.), along section P-O (Fig. 3)

(a)	All Sites	n
Woodland	1.06 ± 0.053	16
Ephemeral swamp	1.17 ± 0.165	12
Perennial swamp	1.91 ± 0.233	5

For difference between woodland and perennial swamp t = 5.0, P<0.001 and between ephemeral and perennial swamps t = 2.3, P<0.05.

(b) Woodland and Ephemeral Swamp Sites

N-facing	n	S-facing		n	
1.1 ± 0.06	15	0.8 ± 0.09	t = 3.1	9	P<0.01

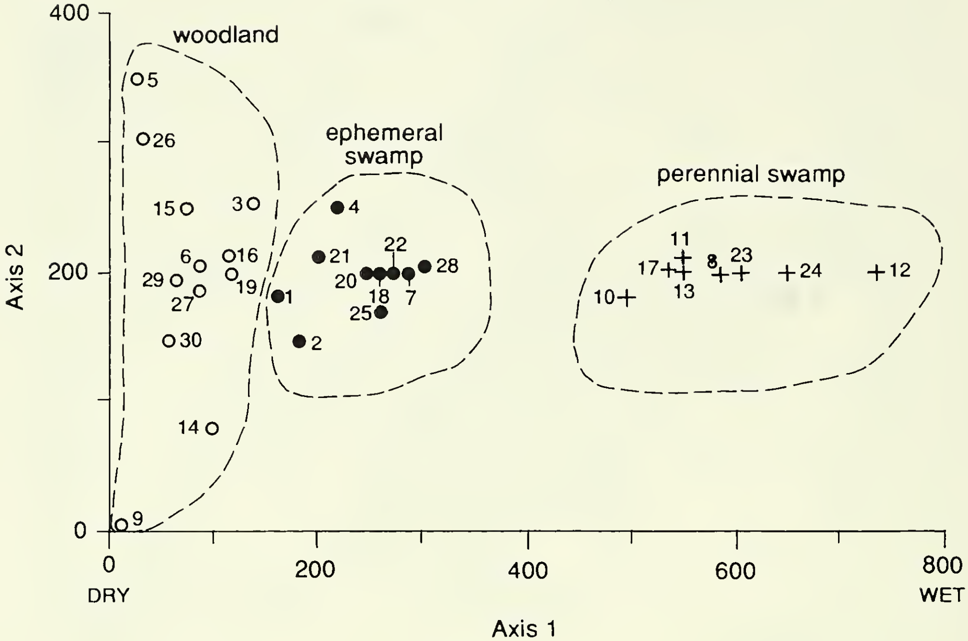

Fig. 6. Ordination of vegetation site data on axes 1 and 2 of DECORANA analysis; woodland (open circle), ephemeral swamp (closed circle) and perennial swamp (cross). Axis 1 is interpreted as a moisture/drainage gradient.

7). After the 1982 fire, species richness increased on both aspects but the relative differences became apparent 3 years after the fire. Ground cover on south-facing slopes reached pre-fire levels 3 years after the fire, but only to half the pre-fire north-facing levels (Table 4, Fig. 7). Some species were noted only at north or south facing sites (Table 3).

Soils were deeper on north-facing slopes than on the south-facing slopes along section P-O (Table 2**b**) and the means are significantly different. From using bars to penetrate the soil to bedrock, the north-facing holes were found to be less compact (i.e. easier to penetrate) than those facing south.

The inclination of ten trees recorded for each woodland site showed a tendency for the trees to lean downslope, presumably in response to soil creep (60% to 90% of the total observations for each station, gave readings within ±90° of the ground slope bearing). The dominant westerly winds also appear to have influenced the trunks since many trees were inclined towards the east. The sun also seems to play a part in the direction of lean as a number of trees on south-facing slopes were observed to reverse their direction (i.e. head towards the north), above two metres from the ground.

Holland (1974) proposed the terms valley-side and valley-floor swamps, differentiated by their depth of fill and location, but new terminologies, based on hydrology and vegetation, are proposed here: *perennial swamp*, where the water supply is virtually constant and vegetation is dominated by *Gymnoschoenus*; *ephemeral swamp*, where the water supply is irregular and vegetation is characterized by *Lepyrodia*.

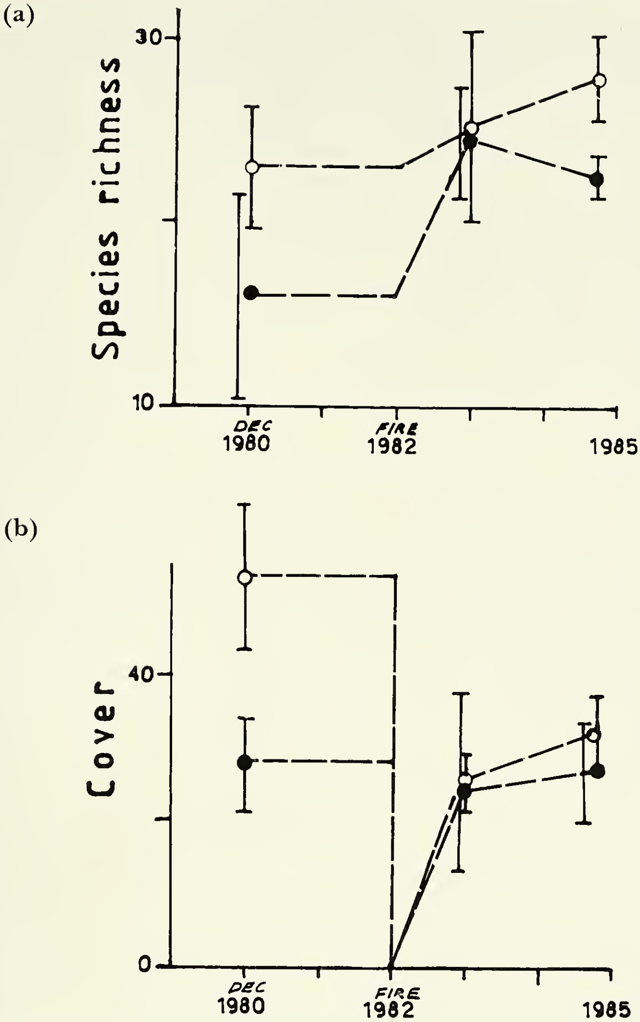

Fig. 7. Woodland understorey species richness (species/$4m^2$) and cover (%) for north (open circle) and south (closed circle) facing slopes before and after fire. Bars indicate 95% confidence intervals with south-facing site offset to left.

Temporal Changes

The major change in the vegetation during the period of the study resulted from the 1982 bushfire that burnt the entire valley, scorching the crowns of the tallest trees and blackening the swamp to ground level. Many species resprouted after the fire and the major pre-fire patterns appeared to quickly re-establish. Some species previously unrecorded during the study were noted, while some other species occupied a wider range of sites. In particular *Hakea teretifolia* seedlings appeared in the perennial swamp where adults had previously been absent. The longer term effects of the fire have not been followed up at this stage.

As with landforms, temporal changes to soils, which are complex and difficult to determine, are not included in this study.

TABLE 3

Plant species and frequencies in three habitats: woodland (12 sites), ephemeral swamp (10 sites) and perennial swamp (8 sites); and occurrence on north/south aspects. Nomenclature follows Jacobs and Pickard (1981)

Species	Perennial swamp	Ephemeral swamp	Woodland	Aspect
Acacia obtusifolia			8	S
Acacia terminalis			42	N S
Actinotus minor		20	8	N S
Amperea xiphoclada		10	8	S
Baeckea linifolia	100			N S
Banksia spinulosa			33	N
Baumea gunnii	25			N S
Billardiera procumbens			17	N S
Boronia ledifolia			67	N S
Boronia microphylla			8	N S
Bossiaea ensata			17	N
Bossiaea heterophylla		40	67	N S
Cassytha pubescens		50	67	N S
Caustis flexuosa			42	N
Caustis pentandra			8	N
Chionochloa pallida		10	17	N S
Conospermum taxifolium		20		S
Conospermum tenuiflorum		20	25	N S
Dampiera stricta		90	58	N S
Danthonia sp.			8	N
Daviesia ulicifolia		50	92	N S
Dillwynia sericea		10		S
Empodisma minus	100	10		N S
Entolasia stricta		10		N S
Epacris microphylla		50		S
Epacris obtusifolia	38	20		N S
Epacris pulchella			8	S
Eucalyptus piperita			42	N
Eucalyptus sclerophylla			50	N S
Eucalyptus sieberi			8	S
Eucalyptus stricta		10		S
Gahnia microstachya			17	N S
Gahnia sp.			42	N S
Gompholobium latifolium			8	S
Gonocarpus tetragynus		20	25	N S
Gonocarpus teucrioides	13	40	8	N S
Goodenia belledifolia	13	70	50	N S
Grevillea laurifolia			8	N S
Grevillea sericea		30	58	N S
Gymnoschoenus sphaerocephalus	88			N S
Haemodorum planifolium		10	17	N S
Hakea dactyloides		40	25	N S
Hakea teretifolia	38	50	8	N S
Hibbertia cistiflora		10		N S
Hibbertia empetrifolia		10	25	N S
Isopogon anemonifolius		30	25	N S
Kunzea capitata	25			N S
Lambertia formosa		10	58	N S
Lepidosperma limicola	75			N S
Lepidosperma viscidum		30		N S
Leptospermum attenuatum		80	50	N S
Leptospermum flavescens		10		S
Leptospermum lanigerum	13			S
Leptospermum squarrosum	38	20		N S

TABLE 3 (Cont'd.)

Species	Perennial swamp	Ephemeral swamp	Woodland	Aspect
Lepyrodia scariosa	13	100	17	N S
Lindsaea linearis		50	50	N S
Lomandra cylindrica		40		N S
Lomandra filiformis		10	50	N S
Lomandra glauca		20	58	N S
Lomandra gracilis		10	17	N S
Lomandra longifolia			8	S
Lomandra obliqua		20	75	N S
Lomatia silaifolia			33	N S
Mirbelia rubiifolia		60		S
Monotoca scoparia			8	N
Mitrasacme polymorpha		10		S
Patersonia glabrata		10	75	N S
Patersonia sericea		40	75	N S
Persoonia laurina			8	N
Petrophile pulchella		10	25	N S
Phyllota squarrosa			50	N
Pimelea linifolia			58	N
Platysace linearifolia		40	75	N S
Plinthantheca paradoxa		20		S
Poranthera microphylla			17	N S
Pteridium esculentum			8	S
Ptilanthelium deustum		80	25	N S
Pultenaea divaricata	50			N S
Pultenaea elliptica			25	N
Pultenaea incurvata	13			N S
Schoenus brevifolius		50	17	N S
Schoenus villosus		60	25	N S
Schoenus sp.			8	N S
Selaginella uliginosa	13	10	8	N S
Sowerbaea juncea		10		S
Symphionema montanum		10		S
Tetrarrhena juncea	25	90	50	N S
Tetratheca rupicola			8	N
Thysanotus juncifolius		10		N
Thysanotus tuberosus		10		S
Viola sieberiana			8	N
Xanthorrhoea resinosa			8	N S
Xanthosia pilosa		10	58	N S
Xyris ustulata	63			N S

Hydrology

Spatial Variation

(i) Surface Flow

Perennial creek flow is along a 60 m length above the stepped knickpoint. Elsewhere creeks appear only after heavy rain.

(ii) Groundwater

Height of groundwater table above bedrock increases downslope and downvalley with maximum saturation at site 24 (2.6 m), in the centre of the swamp (Figs. 5, 8, 9). Surface moisture readings show a similar trend (Fig. 10).

Height of groundwater table above bedrock under the woodland is less than for the

TABLE 4

Prefire basal area of tree species

	(a) Mean basal area (m^2ha^{-1}), (± s.e.m.) N-facing	n	S-facing	n
Eucalyptus piperita	26 ± 10.3	9	34 ± 9.8	3
Eucalyptus sclerophylla	22 ± 6.0	9	18 ± 13.8	3
Eucalyptus sieberi	7 ± 3.3	9	21 ± 7.5	3
Total basal area	55 ± 7.3	9	73 ± 5.2	3

	(b) % total basal area N-facing	S-facing
Eucalyptus piperita	47	46
Eucalyptus sclerophylla	40	25
Eucalyptus sieberi	12	28
Total	100	100

ephemeral swamp which in turn is less than for the perennial swamp, in each season (Table 5**a**). Surface moisture readings show a similar trend (Table 6**a**).

A difference in groundwater behaviour for woodland and ephemeral swamps on one hand and perennial swamps on the other is revealed in the relationship between the mean watertable height above bedrock and the range of readings for each site, in all seasons.

Comparing the mean with the range in the woodland and ephemeral swamps, there is a trend that as the mean increases the range also increases. Means for north-facing woodland sites vary from .005 m to .037 m and for south-facing swamp sites from .06 m to .63 m (Fig. 11**a**). The low number of sites preclude testing of the south-facing woodland and north-facing swamp sites. The results suggest that groundwater is free to move within the soil down the valley side within each vegetation unit. At the same time there is likely to be increasing groundwater available from runoff in the downslope direction. No correlation was found between groundwater depth and surface area draining to each site but it is thought that the segmentation of slopes by the claystones and the effect on local groundwater movements could influence this result. The groundwater drains away fairly rapidly, so the greater the resulting water depth from a rain event, the greater the variation or range.

For south-facing perennial swamp sites there is a trend that as the mean increases the range decreases (Fig. 11**b**). The low number of sites precludes testing of the north-facing sites. The swamps tend to accumulate water, particularly on the understeepened reach, and tend to dry out from the periphery. Factors contributing to impedence of drainage include geomorphology (understeepened reach, alluvial bulge, ridges and swales and decreasing valley width downstream), vegetation (closely spaced sedge clumps) and soil (a fibrous peaty texture acts like a sponge). These conclusions on the three separate vegetation units are supported by watertable heights above bedrock measured on 29 November, 1982 during a dry summer period where rainfall for the preceding 30 days was 13 mm and the temperature on the preceding day was 23°C. All the woodland and ephemeral sites had zero water in the holes while in the perennial swamp only site 10 had zero water depth. There was no flow out of the valley and the knickpoint had zero flow. At the same time the watertable height at site 24, in the centre of the perennial swamp, was 2.4 m.

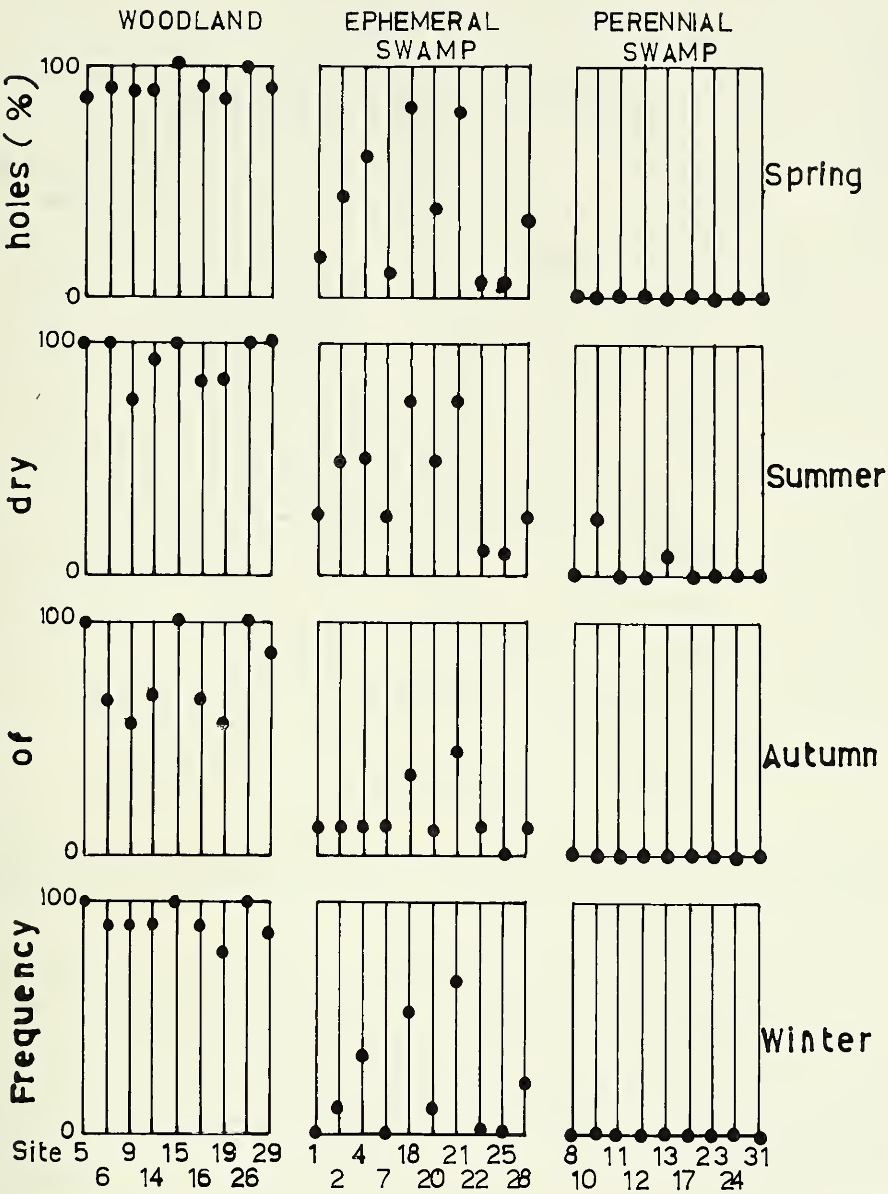

Fig. 8. Frequency that each hole was dry (%) between March, 1982 and December, 1987 for all sites by season and for woodland, ephemeral swamp and perennial swamp.

The maximum height of the groundwater table above bedrock for all woodland sites in each separate season was greater for south-facing sites than for north-facing sites (Table 5**b**). In the perennial swamp the range of groundwater table heights for site 13 (north-facing) was greater than for site 10 (south-facing), in each season (Table 7). Surface moisture on a woodland south-facing site (9) was significantly greater than for a woodland north-facing site (15), sites equally high above the creek (Table 6**b**). Further

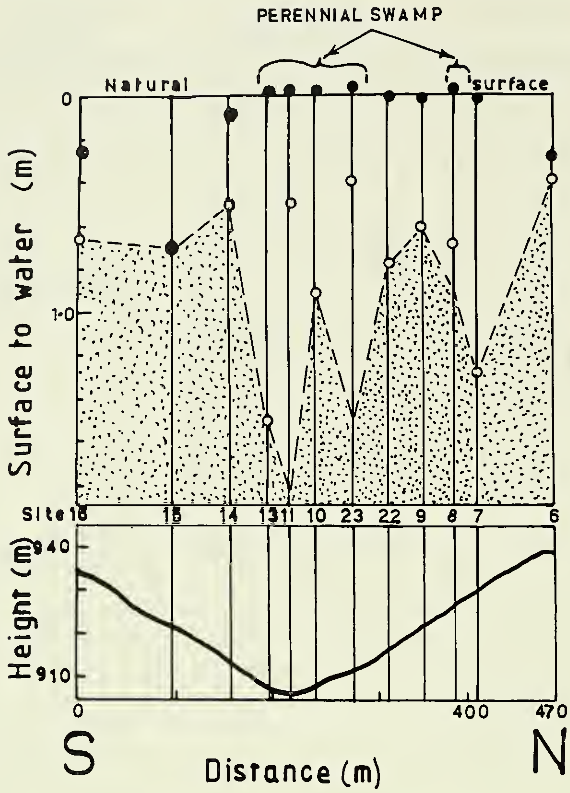

Fig. 9. Sites on section S-N (Fig. 2a) showing ground height (firm line), maximum (closed circle) and minimum (open circle) distance from ground surface to groundwater table level, and distance from ground surface to bedrock (dashed line), all in metres.

TABLE 5

Maximum height of groundwater table above bedrock (m) for vegetation types, March 1982-December 1987: (a) by season, for all sites; (b) by season and aspect (woodland sites only)

(a)	Spring		Summer		Autumn		Winter	
Woodland	0.6		0.5		0.5		0.6	
Ephemeral Swamp	1.9		1.6		1.9		1.9	
Perennial Swamp	2.6		2.6		2.6		2.6	
(b)	N	S	N	S	N	S	N	S
Woodland	0.4	0.6	0.2	0.5	0.4	0.5	0.4	0.6

evidence for moist south-facing slopes is that there are numerous south-facing ephemeral swamps but few face north. This probably results from greater evaporation on the north-facing sites which have higher temperatures than south-facing sites (Holland *et al.*, 1992). Further, woodland north-facing sites 15 and 26 were always dry as water drains rapidly away from them. This may be a function of the relative soil compaction of north and south-facing sites referred to above.

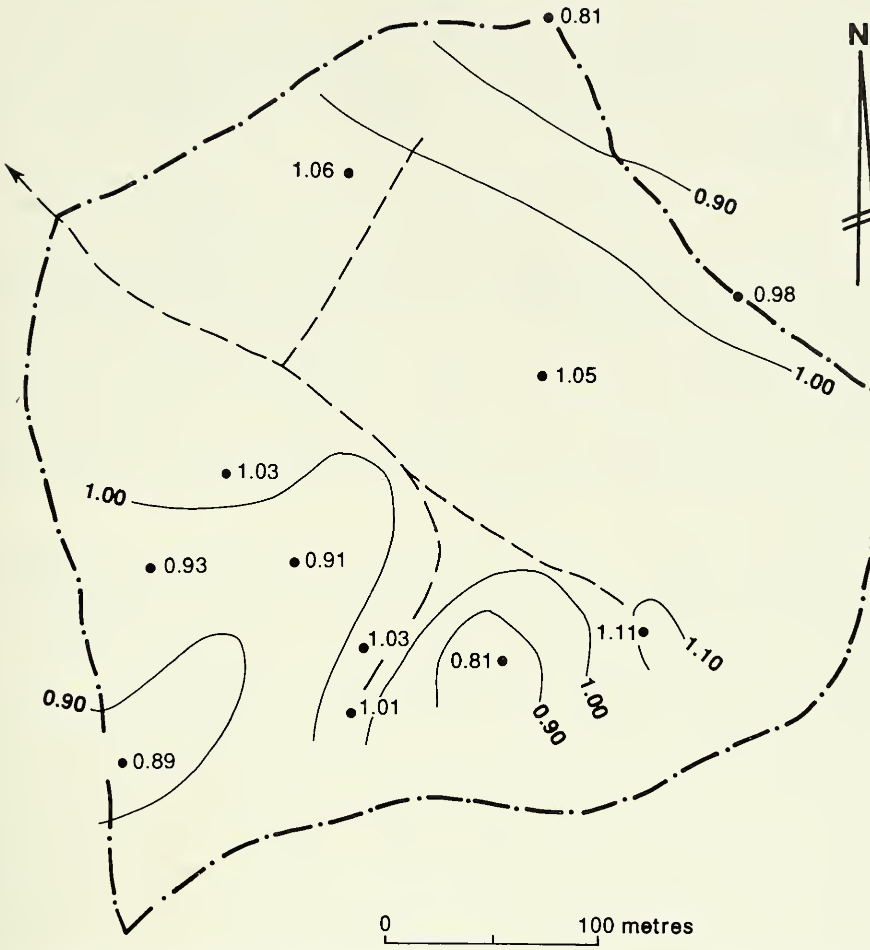

Fig. 10. Morning surface moisture (arbitrary meter units where the lower the reading, the drier the conditions). Iso lines from means of measurements.

TABLE 6

Comparison of mean surface moisture (arbitrary meter units, where lower readings indicate drier conditions) (± s.e.m.) for vegetation type in summer and winter

(a) All sites	Summer	n	Winter	n
Woodland	0.7 ± 0.11	12	0.8 ± 0.10	12
	t = 3.3, P<0.005		t = 2.8, P<0.01	
Ephemeral Swamp	1.6 ± 0.25	10	1.5 ±0.77	10
	t = 7.3, P<0.001		t = 5.3, P<0.001	
Perennial Swamp	7.0 ± 0.69	9	5.1 ±0.63	9
(b) Sites 9 and 15				
S-facing (9)	0.9 ± 0.11	12	1.0 ± 0.13	13
N-facing (15)	0.3 ± 0.05	12	0.4 ± 0.09	13
	t = 4.4, P<0.001		t = 3.2, P<0.005	

TABLE 7

Range of groundwater table height above bedrock (m), by season, for two sites

	Spring	Summer	Autumn	Winter
Site 13 (N-facing)	1.2	1.5	1.1	1.1
Site 10 (S-facing)	0.9	0.9	0.8	1.0

Groundwater movement is influenced by lithological variations and structural features of the rock sequence. Beneath the soil the water seeps through joints, bedding planes or other lines of weakness in the rocks until it reaches a claystone bed. The claystones are aquicludes, but where they pinch out or are breached by joints, water enters the underlying sandstone. Water above an aquiclude emerges on the valley side as springs or as lateral seepage along a valley side knickpoint. These aquicludes control the upper edge of the ephemeral and perennial swamps. The lower edges of the swamps are not subject to such geological controls. Cliffs near the study area reveal that water flows down the joints etc. and where water is not visible ferns and other mesic plants confirm its presence.

From the disposition of Blue Mountain swamps it is clear that water emerges above an aquiclude not only in the dip direction but in any other direction as well. However, there is a tendency for swamps to form most frequently on the sides of the valleys below a dipping claystone (Holland, 1974). The study valley dips to the east, though it drains to the west, so some of its groundwater probably seeps eastwards out of the valley. This was tested by measuring creek flow simultaneously at the stepped knickpoint and on the Wentworth Creek tributary to the east of Cold Foot Creek (Fig. 1). The flow in Cold Foot Creek on 8 December, 1987 at 1100 hours was 0.27 Ls^{-1} and at W 0.16 Ls^{-1}. The Cold Foot Creek catchment is 11.3 ha while the area above W is 3.6 ha. Given the disparate catchment sizes the flow at W is higher than expected suggesting that water enters the catchment from the study area. Furthermore, the vegetation upstream from W supports species indicative of moist conditions (*Callicoma*, *Gahnia*, *Blechnum*), though species on the interfluve of Cold Foot Creek indicate much drier conditions. Also, a swamp near W is perennial while swamps at the same elevation in Cold Foot Creek are ephemeral.

Seasonal Changes

(i) Surface Flow

Flow at the knickpoint ranged from 8.62 Ls^{-1} (28 October 1985) to zero (28 September 1980, 4 January 1981 and 29 November 1982) (Table 8). The highest discharge was when rainfall was high and temperature low. There were zero discharges on three occasions, each associated with high temperature and low rainfall. Except in high flows the water is clear since swamp vegetation effectively sieves the water. Water at the knickpoint, on 30 September 1985, at 1100 hours (flow 0.66 Ls^{-1}) contained less than 1 mgL^{-1} f sediment. The highest seasonal discharge was in spring and lowest in summer (Table 8). The low summer discharge is related to a low rainfall figure but high temperature. Much of the perennial swamp surface is ponded and susceptible to evaporation with high temperature.

Another factor affecting discharge rates is the emergence of spring water (sites 8, 23) after possibly long periods under the surface. There were substantial flows at these springs whenever they were observed.

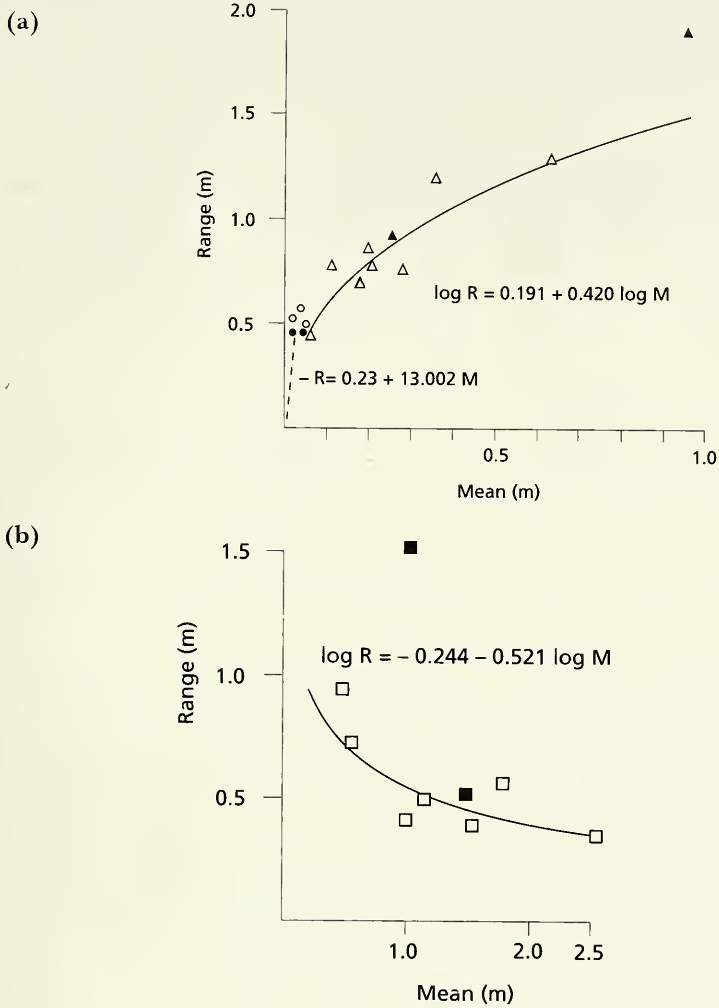

Fig. 11. Regressions of range of watertable height above bedrock (m) on mean watertable height above bedrock (m), in all seasons. (a) for north-facing woodland sites (closed circles and dashed line), where range = .023 + 13.002 mean, n = 6 and r^2 = .96; and south-facing ephemeral swamp sites (open triangles and firm line), where log range = .191 + .420 log mean, n = 8, and r^2 = .80. (b) for south-facing perennial swamp sites (open squares and firm line), where log range = -.244 + -.521 log mean, n = 7 and r^2 = .70.

Open circles are south-facing woodland sites, closed triangles north-facing ephemeral swamp sites and closed squares north-facing perennial swamp sites.

(ii) Groundwater

Woodland sites usually contain groundwater only after heavy rain (Fig. 8). They were dry over 70% of the time if figures for autumn (wettest season) are excluded (Table 9). In the ephemeral swamps the groundwater table rises rapidly after rain but soon soaks away. Perennial swamp sites were always wet (with the exception of 10 which was dry twice in spring and five times in summer, and 13 which was dry twice in summer).

The effect of evaporation, related to high summer temperatures is clear. Minimum mean groundwater table height above bedrock is in summer, even though the mean summer rainfall is higher than in winter (Table 9). The highest mean groundwater table heights occurred in autumn, coinciding with maximum seasonal rainfall. There is a similar result in the woodland, ephemeral swamp and perennial swamp.

TABLE 8

Knickpoint discharges (Ls^{-1}): (a) overall highest and lowest recorded, with rainfall (mm) for the preceding 30 days and maximum daily temperature (°C) for the previous day (Katoomba meteorological station); (b) highest seasonal values

(a)	Highest		Lowest	
Discharge (Ls^{-1})	8.7	0	0	0
Rainfall (mm)	420	9	13	84
Temperature (°C)	12.4	21.2	23.3	27.6

(b)	Discharge (Ls^{-1})	Rainfall (mm)	Temperature (°C)
Spring	8.7	420	12.4
Summer	4.8	110	25.0
Autumn	7.0	338	14.9
Winter	5.0	187	5.1

TABLE 9

Frequency of dry holes (%) between March, 1982 and December, 1987 for all sites, by season and for woodland, ephemeral swamp and perennial swamp together with mean monthly rainfall (R) (mm) at Katoomba meteorological station

Season	Woodland	Ephemeral Swamp	Perennial Swamp	R (mm)
Spring	91.5	43.3	1.1	133
Summer	93.9	49.3	5.3	110
Autumn	82.9	18.5	0	145
Winter	93.5	35.0	1.0	106

Daily Changes

(i) Surface Flow

Discharges at the knickpoint fell during the day and rose at night. Because of the low flows from the small drainage basin, these minute changes are easily detected where water flows over bare rock. The changes are demonstrated using measurements taken over several days, during rainless periods, when discharges were steadily decreasing (Table 10, Fig. 13). The falls during the day clearly related to evaporation, particularly in the ponded swamp. At night the discharge rose as the evaporation rate declined but groundwater continued to enter the creek. After sunrise there was a delay of about 3 hours before the discharge rate fell. It rose again about sunset (Fig. 13).

(ii) Groundwater

Groundwater table levels tended to fall during the day and rise at night. This is demonstrated by levels for site 10 measured over several rainless days in summer and winter. Here the daily peaks fell throughout the period of measurement but the levels oscillated each day and night and the difference between the means of the day and night fluctuations were significant (Fig. 12, Table 11). The precise mechanism is not known but clearly results from a balance between gains of water from above the aquiclude and losses from evaporation of surface and underground water, together with loss of water by downslope drainage. The changes occurred even when groundwater table level was 0.7 m below the surface. Maximum changes were noted in the swamp sites below the woodland margin e.g. 10, 13 and 31.

TABLE 10

Knickpoint discharge (Ls^{-1}) 1987, during rainless periods of several days, when discharges were steadily decreasing

(a) Overall Variation

	Summer		Winter	
Sunrise	3 December	0.6	22 June	1.9
Sunrise	9 December	0.2	1 July	0.3

(b) Daily and Nightly Variation, means (± s.e.m.)

		n		n
DAY (sunrise-sunset)	−0.18 ± 0.035	9	−0.10 ± 0.026	7
NIGHT (sunset-sunrise)	+0.12 ± 0.030	10	+0.07 ± 0.024	8
	t = 6.2, P<0.001		t = 4.2, P<0.001	

There was a correlation between groundwater table levels and diurnal fluctuations in weather, as indicated by temperature. This is demonstrated by comparing changes in groundwater table level for site 10 with temperature changes over several days (Fig. 12), and during the course of one 24-hour period (Fig. 13). Note also that surface moisture also falls in response to evaporation during the day. Groundwater table levels rose during the night but started to fall again about three hours after sunrise i.e. when the temperature reached 13°C and relative humidity was 95%. Surface moisture fell during the night until midnight then rose again until three hours after sunrise, when it fell again. Also, falls were greater in summer than in winter (Table 11). Regressions of distance below the surface to groundwater table level, on surface temperature for one summer day for a south-facing site (10) and a north-facing site (13) are each statistically significant. They show differences between these sites (Fig. 14**a**, **b**). Temperatures at site 13 are generally higher than for site 10 (Holland *et al.*,1992) and the rate of fall of groundwater table level for 13 is generally greater than for site 10, probably from high evaporation on site 13. A significant difference was found when paired readings were taken on 23 December, 1987 (mean = 0.22 $mday^{-1}$ ± s.e.m. 0.027, n = 6, t = 8.1 & P<0.001).

TABLE 11

Mean rise (+) and fall (−) of groundwater table level ($mday^{-1}$) at site 10, (± s.e.m.) in June/July and December 1987. Rates taken in summer between nightly peaks and daily lows, in winter between sunrise and sunset. Temperature (°C) is daily maximum recorded on first day of sampling

	Day	n	Night	n		Temp (°C)
Summer	− 0.18 ± 0.023	5	+ 0.11 ± 0.011	5	t = 3.9, P<0.005	26
	t = 5.6, P<0.001		t = 9.4, P<0.001			
Winter	− 0.03 ± 0.006	5	− 0.01 ± 0.002	5	t = 2.9, P<0.027	7

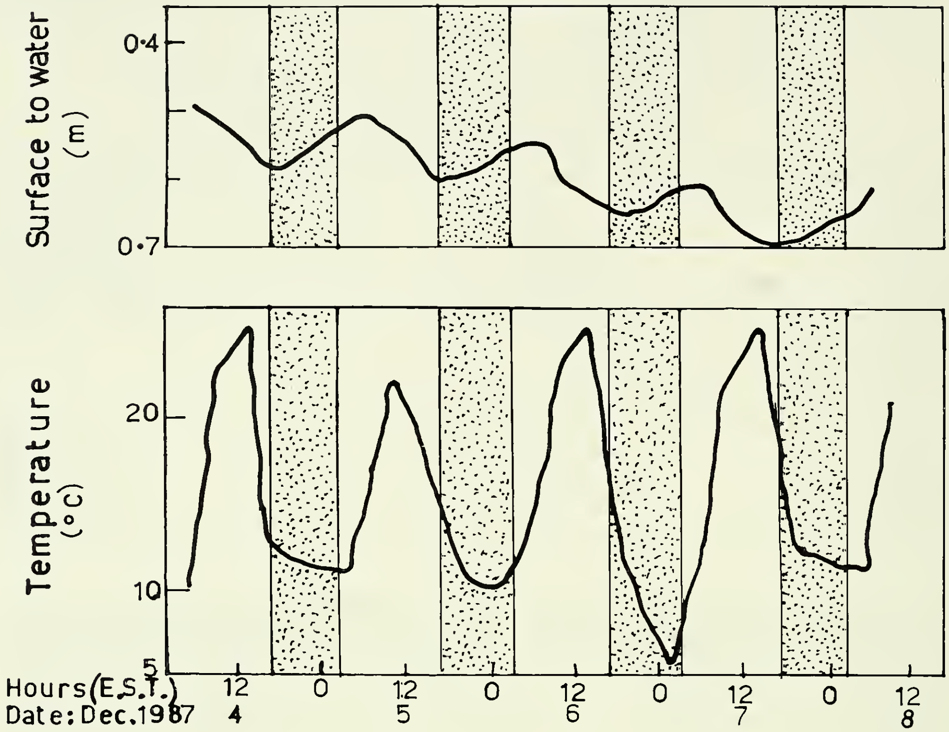

Fig. 12. Groundwater table depth (m) and surface temperature (°C), for day/night (hatched) in December 1987 at site 10. Day/night defined by sunrise and sunset.

Discussion

Studying differences between individual components across a range of factors is a useful tool for investigating complex environmental relationships. This study has examined spatial and temporal variation in geology, geomorphology, vegetation, soils and hydrology.

Spatial differences reveal the gross shape of the present landform, which is being continually modified. The landform is largely a response to surface erosion over a long period, probably extending back at least to the last uplift in the Blue Mountains. This has resulted in a gentle upland valley. However, geologic controls modify many of the surface features, for example claystone beds result in the valley side knickpoints which segment the valley into its valley-in-valley form. These beds also influence the landforms by controlling the amount and movement of groundwater at each site. Examples of this are the swamps, the alluvial bulges and the diversion of water into adjoining Wentworth Creek.

This study has not examined temporal changes in the landforms, though Holland (1974) found that the shallow valley fill of a perched headwater valley could be up to 17,000 years old and that erosion of the fill may have proceeded upstream from the

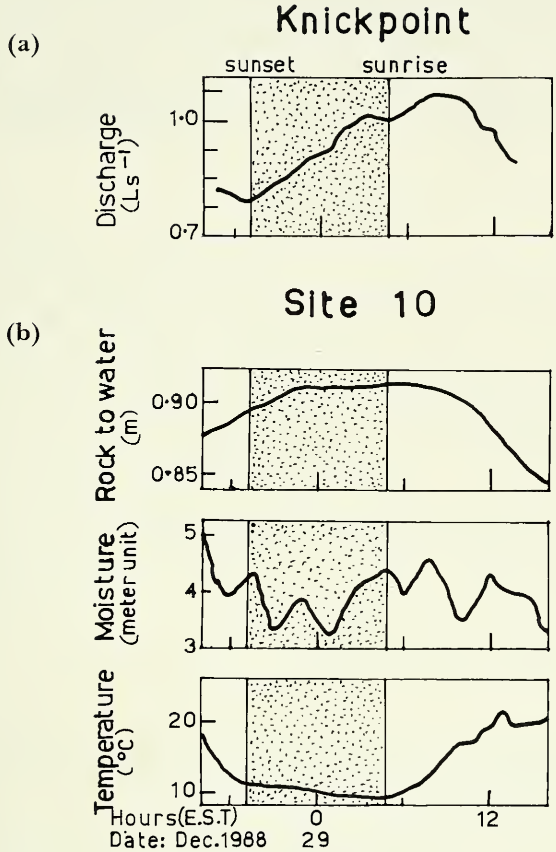

Fig. 13. Events during 24-hour rainless period (28-29 December 1988) when flow falling: (a) discharge at stepped knickpoint; (b) heights of groundwater table above bedrock, surface moisture (arbitrary meter units where the lower the reading the drier the conditions) and surface temperature at site 10.

stepped knickpoints with subsequent infilling of sediment. It is conceivable that these valleys could have a history of similar cuts and fills prior to 17,000 years ago.

Spatial patterns of vegetation are largely controlled by geology and hydrology. The woodland, ephemeral swamp and perennial swamp are partially delineated by claystone beds and floristic and structural differences can be related to the amount and movement of groundwater. Temporal changes are more difficult to document. Short-term changes, over days and weeks have not been examined. Hydrologic changes occur not only daily but hourly, in response to changing weather conditions.

The study found that groundwater table levels fell during the day as a function of increasing temperature. Further, it was established that different sites had different rates of water movement, related to the individual temperature characteristics of each site.

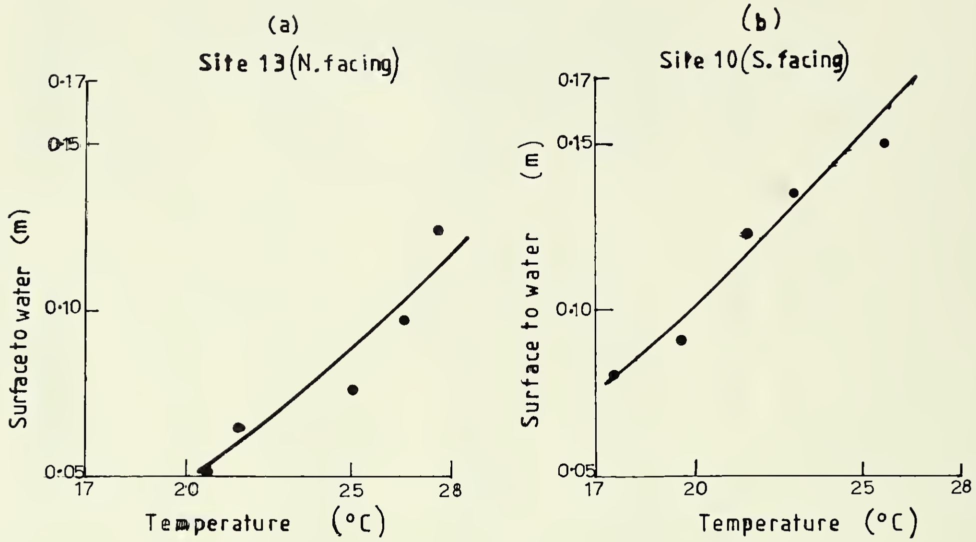

Fig. 14. Regressions of distance between the surface and groundwater table level (m) on surface temperature (°C), in summer (23 December 1987): (**a**) for sites facing north (13); (**b**) for sites facing south (10).

Seasonal changes affect evaporation rates which probably influence erosion. Seasonal vegetation changes include the flowering of species and annual growth cycles. Periodic events include phenomena such as bushfires which can affect vegetation, soils and landform (Selkirk and Adamson, 1981).

North-facing slopes are generally less steep than south-facing slopes. There is some evidence that soils are deeper, less compact, and dry out faster on north-facing slopes. Geological structure appears to play no part, since the beds dip to the east. Asymmetry is found in both swamps and the woodland so is independent of vegetation cover. Within the woodland north and south-facing slopes show differences in tree growth (greater basal area on south-facing) and ground cover (greater species richness on north-facing slopes). As the result of soil creep most trees lean downhill, though the upper trunks of some trees on south-facing slopes curve back towards the north. Some differences were also noted in daily groundwater table heights and on seasonal surface moisture and groundwater table heights on north or south-facing slopes. Because of the wide ranging nature of these north/south differences, it is assumed that solar radiation is the main factor responsible for the asymmetry.

Our other paper (Holland *et al.*, 1992) extends the present findings by examining calculated solar radiation and temperature variations in the valley and relates these to long-term changes in the landscape.

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References

BUNTING, B. T., 1960. — Bedrock corrosion and drainage initiation by seepage moisture on a gritstone escarpment in Derbyshire, *Nature* 185: 447.

GAUCH, M. G., 1982. — *Multivariate Analysis in Community Ecology*. Cambridge: Cambridge Univ. Press.

GOLDBERY, R., 1966. — The geology of the Upper Blue Mountains area. Kensington, N.S.W.: University of New South Wales, B.Sc. (Hons.) thesis, unpubl.

——, and HOLLAND, W. N., 1973. — Stratigraphy and sedimentation of redbed facies in Narrabeen Group of Sydney Basin, Australia, *Am. Assoc. Petroleum Geologists Bull.* 57 (7): 1314-1334.

HOLLAND, W. N., 1968. — A study of longitudinal profiles in an area of the Blue Mountains, New South Wales. Sydney, N.S.W.: University of Sydney, M.A. Qualifying Rept., unpubl.

——, 1974. — Origin and development of hanging valleys in the Blue Mountains, New South Wales. Sydney, N.S.W.: University of Sydney, Ph.D. thesis, unpubl.

——, 1977. — Slot valleys. *Australian Geographer* 13: 338-339.

——, BENSON, D. H., and MCRAE, R. H. D., 1992. — Spatial and temporal variation in a perched headwater valley in the Blue Mountains: solar radiation and temperature. *Proc. Linn. Soc. N.S.W.* 113 (4): 297-310.

——, and PICKUP, G., 1976. — Flume study of knickpoint development in stratified sediment. *Geol. Soc. Am. Bull.* 87: 76-82.

JACOBS, S. W. L., and PICKARD, J., 1981. — *Plants of New South Wales*. Sydney: Govt. Printer.

KEITH, D. A., and BENSON, D. H., 1988. — The natural vegetation of the Katoomba 1:100 000 map sheet. *Cunninghamia* 2: 107-143.

MCELROY, C. T., 1952. — Contour trench formations in upland plains of New South Wales, *J. Roy. Soc. N.S.W.* 85: 53-62.

SELKIRK, P. M., and ADAMSON, D., 1981. — The effect of fire on Sydney sandstone. *In* STANBURY, P. (ed). *Bushfires: Their Effect on Australian Life and Landscape*. Sydney: Macleay Museum.

STOCKTON, E. D., and HOLLAND, W. N., 1974. — Cultural sites and their environment in the Blue Mountains. *Archaeol. Phys. Anthrop. Oceania* 9: 36-65.

THORNBURY, W. D., 1954. — *Principles of Geomorphology*. New York: John Wiley & Sons.

YOUNG, A. R. M., 1982. — Upland swamps (dells) on the Woronora Plateau, N.S.W. Wollongong, N.S.W.: University of Wollongong, Ph.D. thesis, unpubl.